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Advanced low NO_x combustion using highly preheated air

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Abstract

Flameless combustion or *invisible flame* in regenerative furnaces using highly preheated air has recently received much attention for its accomplishment not only in energy saving, but also for low nitric oxide emission. The characteristics of combustion with highly preheated air were studied to understand the change of combustion regime and the reason for the compatibility between high performance and low nitric oxide emission. It was found that combustion was sustained even in an extremely low concentration of oxygen, if the combustion air were preheated higher than the auto-ignition temperature of the fuel. As an application of the principle, we can reduce nitric oxide emission by dilution of the combustion air with plenty of recirculated burned gas in the furnace. Dilution makes the oxygen content of the oxidizer low, which decreases temperature fluctuations in the flame as well as the mean temperature, hence, low nitric oxide emission. Finally, the applicability of highly preheated air combustion to other fields than industrial furnaces has been discussed.

Keywords: Preheated air; Regenerative combustion; Energy saving; Thermal efficiency; Nitric oxides; Furnace

1. Introduction

Heat energy necessary for our daily life is mostly produced by combustion. Combustion efficiency is sufficiently high in most cases, but the efficiency of heat utilization is not always high enough. To raise the thermal efficiency of industrial furnaces, such as melting furnaces or reheating furnaces, heat recirculation from high temperature waste gas to the fresh combustion air has been a typical measure. We call it heat recirculating combustion, which has been realized with a heat exchanger or a recuperator to improve the thermal efficiency of the system. Therefore, combustion with preheated air is not new as a technology or a concept to save energy.

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However, *flameless combustion* [1] or *invisible flame* in regenerative furnaces using highly preheated air has recently received much attention for its amazing accomplishment not only in energy saving, but also for low nitric oxide emission as a result of the new development of high frequency alternate flow type regenerative furnaces [2]. *Highly preheated air* in those cases typically denotes preheated air temperature higher than approximately 1000 K, which is far too high for the former types of heat recovery system.

The formation and destruction mechanisms of nitric oxides have been clarified through the valuable experimental and kinetic researches, and it has been commonly understood that nitric oxides in the exhaust increase with the temperature rise of combustion air. Therefore, it has been considered as a sort of trade-off issue to accomplish energy saving and low nitric oxide emission in heat recirculating combustion. Nevertheless, to solve these incompatible demands was a main goal of the project on the development of high performance industrial furnaces supported by NEDO (New Energy and Industrial Technology Development Organization), and considerable advancements have been achieved in theory and practice.

In the present work, we discuss the reason why nitric oxide emission can be decreased even by the use of highly preheated combustion air, and the necessity of new combustion controls to generate an appropriate combustion regime as well.

2. Heat recirculating combustion

Preheating of a combustible mixture by recycled heat from exhaust gases has been considered an effective method for combustion of low caloric fuel or ultra-lean mixtures. Many related researches were performed in the past [3–7], and the concept of heat recirculating combustion was clearly demonstrated by Weinberg et al. [5] in the famous Swiss-roll burner. Heat transfer from burned products to the unburned mixture occurs through double-roll walls separating the products and the mixture. Fig. 1 shows the temperature histories of premixed combustion with

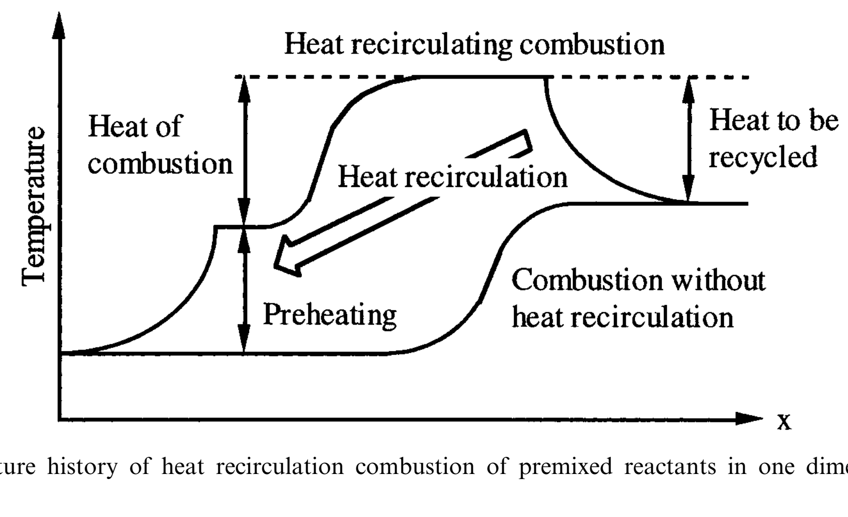

Fig. 1. Temperature history of heat recirculation combustion of premixed reactants in one dimensional adiabatic system [4].

and without heat recirculation in an adiabatic system. If it were a completely adiabatic system, the outlet temperature of the burned gas would be the same regardless of the heat recirculation. Adding this fact, the maximum temperature level in heat recirculating combustion is determined by the temperature and amount of recycled heat, which is independent of the equivalence ratio of the mixture or the caloric value of the fuel used. The concept is true for premixed combustion, but not always so for non-premixed or diffusion combustion in furnaces. This is the most important point when we consider highly preheated air combustion in practical systems.

Excess enthalpy combustion studied in the past has often been intended to sustain stable combustion in the mixture of low caloric fuel or an ultra-lean mixture which is far from flammable at atmospheric temperature. Therefore, combustion follows the temperature rise of the mixture to an elevated level by heat recirculation and by the use of radiative heat transfer, as well as heat convection or heat conduction [8–14]. Fig. 2 shows the combustible domain expressed by equivalence ratio, caloric value of fuel and mixture temperature. At normal ambient temperature, an ordinary hydrocarbon gaseous fuel mixed with atmospheric air exhibits a combustible domain around the stoichiometric composition, and an increase of temperature of the mixture expands the combustible domain significantly. If we want to use a low caloric fuel, in contrast, the combustible domain disappears at ambient temperature and starts to reappear when the mixture is preheated to a certain temperature level. Thus, we can understand that the excess enthalpy combustion of low caloric value fuel or an ultra-lean mixture is a method to bring the mixture from outside of the combustible domain into the inside by heat recirculation.

In practical furnaces, diffusion or non-premixed combustion is more common because of its safety and controllability. Recycled heat from the exhaust gas is utilized for heating the combustion air instead of the mixture. In the past, this technology was first applied to the glass and cement industries, where high temperatures were essentially required, and preheated air of 873 K was utilized by a recuperative burner. In this case, the preheat resulted in a reduction of fuel input rate by 30% [16]. Subsequent improvement in materials has permitted higher preheat, and glass

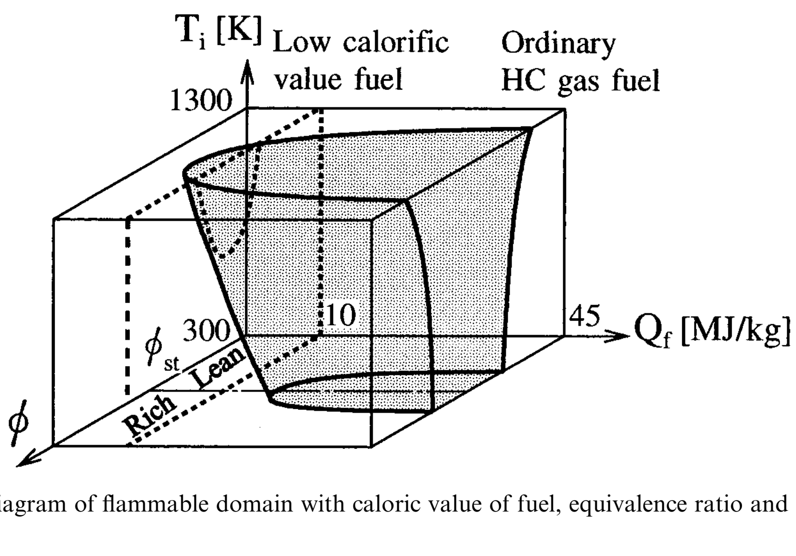

Fig. 2. Schematic diagram of flammable domain with caloric value of fuel, equivalence ratio and air temperature [15].

melting regenerative furnaces have been working with preheated air exceeding 1273 K. The reduction of fuel consumption in this case reached 50% [17].

It has been held that the combustion reaction takes place near-stoichiometric during the mixing process of fuel and air when we adopt non-premixed combustion, even if the excess air ratio is quite high, and the near-stoichiometric flame temperature produces large amounts of nitric oxides when it is preheated. Therefore, as exemplified in Fig. 3, we cannot help but stop preheating the air so that the nitric oxide emission does not violate air quality regulations, even though more energy saving is expected by higher preheating. If the regulation for nitric oxides becomes more strict, the consistency of energy saving by heat recirculation and low nitric oxide emission would be more difficult. Therefore, development of low nitric oxide combustion technology using non-premixed flame would be one of the most important subjects in heat regenerative combustion.

Many researches and efforts have been made to satisfy these two incompatible requirements simultaneously [18–24]. Among them, a high frequency alternating flow regenerative furnace, the basic concept of which is shown in Fig. 4, is one of the most successful systems in which remarkable energy saving can be achieved without emitting high concentrations of nitric oxides [24]. The system consists of two sets of a ceramic honeycomb regenerator and a burner. Since they are operated alternately every minute or so, an extremely high heat exchange coefficient is achieved by the effect of unsteady heat transfer in the honeycomb regenerator, where the flow direction of the exhaust gas and fresh air alternates against each other.

In practice, we can preheat the combustion air up to almost the exhaust gas temperature resulting in a sufficiently low temperature of the outgoing exhaust gas. Therefore, preheated air higher than 1273 K can be easily obtained compared to other types of heat recovery devices, and

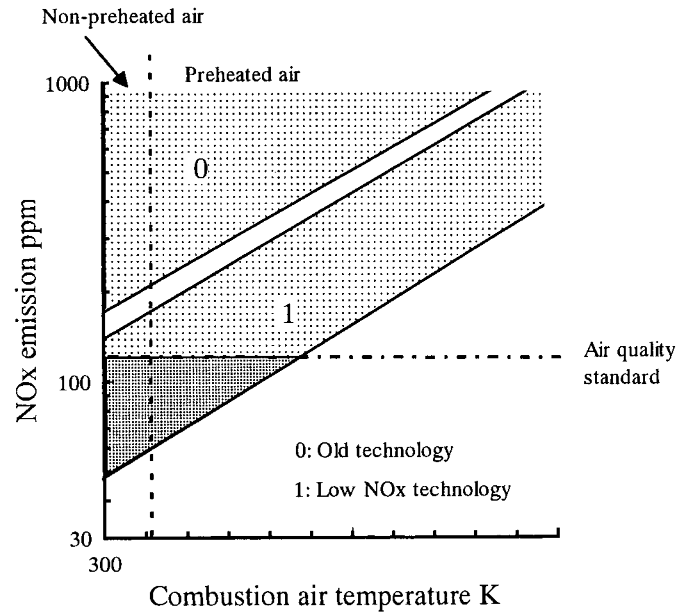

Fig. 3. Correlation between combustion air temperature and nitric oxide emission.

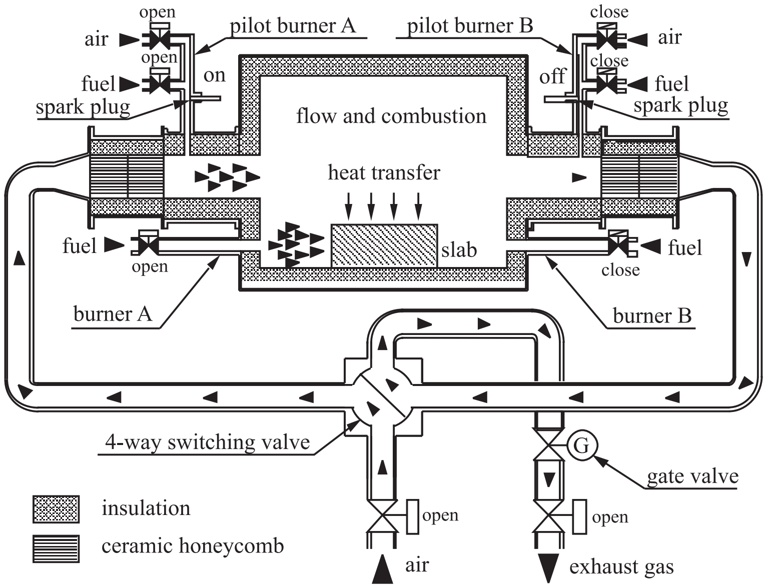

Fig. 4. Schematic structure of heat recirculating furnace operated with high frequency alternating flow regenerators.

this fact suppresses the heat loss in the exhaust. We did not consider in the past that the utilization of such high temperature combustion air is consistent with low nitric oxide emission technology. However, the experimental facts were reported that the combination of direct injection of fuel into the furnace and the high momentum ejection of staging air resulted in unexpected low nitric oxide emission. Therefore, it is our main object to clarify the relation between highly preheated combustion air and the resultant low nitric oxide emission.

3. Auto-ignition temperature of fuel

When a fuel mixes with combustion air, some heat is necessary to initiate combustion. Therefore, a recirculating flow of combustion products behind a flame holder or a pilot flame is frequently utilized in furnace combustion to stabilize flames. However, if the combustion air is sufficiently preheated, combustion follows instantly upon the mixing of the two reactants anywhere in the furnace. Considering combustion of natural gas with atmospheric air, auto-ignition will occur when the preheating temperature of air exceeds approximately 1100 K, and for lower preheating temperatures, a forced ignition and a flame stabilizer will be necessary for stable combustion as in the furnace described above.

Shown in Fig. 5, as the oxygen content decreases by dilution with inert gas, such as carbon dioxide or nitrogen, the auto-ignition limit in terms of air preheating temperature rises slightly, but the forced-ignition limit rises significantly. In other words, as the air preheating temperature goes down, it becomes more difficult to stabilize the flame in low oxygen circumstances. For an oxygen content lower than roughly 15% in the diluted air, the combustible region for forced

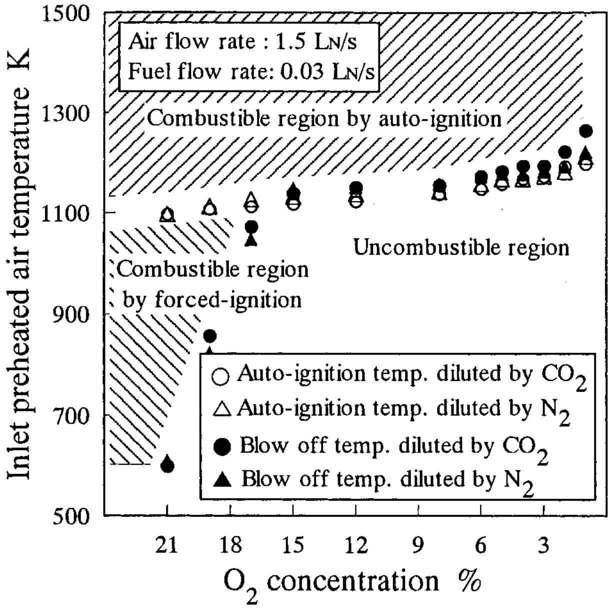

Fig. 5. Auto-ignition limits and blow-off limits for natural gas in a preheated air or a diluted air with CO_2 or N_2.

ignition disappears and only auto-ignition occurs when the diluted air is extremely preheated. From these experimental data, we have obtained new knowledge of the combustion characteristics of gaseous fuels under low oxygen content circumstances, which had not been paid much attention from a practical point of view. The point is that we can burn a gaseous fuel even in quite low oxygen content condition, such as vitiated or diluted air, if its temperature is sufficiently high.

Although too large an amount of exhaust gas recirculation may cause flame extinction when we apply ambient air as an oxidizer, preheating of the combustion air above the auto-ignition temperature of the fuel ensures complete combustion, even with an intense exhaust gas recirculation. Therefore, we would like to call this type of combustion *highly preheated air combustion* as distinguished from *preheated air combustion* in which a conventional burner technology must be applied and auto-ignition does not occur. In contrast, no measure to stabilize a flame is necessary in highly preheated air combustion.

4. Nitric oxide production and flame temperature

Emissions from continuous combustion systems have been intensively investigated in the past, particularly regarding gas turbine engines [25,26]. Consequently, temperature rise in combustion air has been recognized as one of the influencing factors on nitric oxide emission from combustors. Actually, an exponential increase in nitric oxide emission was observed for the temperature rise from 300 to 800 K [25]. This is commonly understood among combustion engineers as an

influence of combustion air temperature on nitric oxide emission because it generally causes higher flame temperature and more nitric oxide emission.

Notwithstanding these facts, it was reported, as mentioned previously, that the nitric oxide emission from a newly developed high frequency alternating flow regenerative furnace was found to be considerably low, even though it was operated with highly preheated combustion air. It was not easy to explain the reason based on established knowledge on the formation and destruction kinetics of nitric oxides. However, we obtained experimental results showing that the nitric oxide emission changed significantly depending on the mixing processes between the fuel and air, keeping their flow rates and temperatures constant.

Fig. 6 shows the combustion chamber used in the experiment. The chamber was designed so that the incoming highly preheated air formed a large recirculating flow. Natural gas was injected from one of the four nozzles shown in the figure, and the nozzle hole was oriented toward

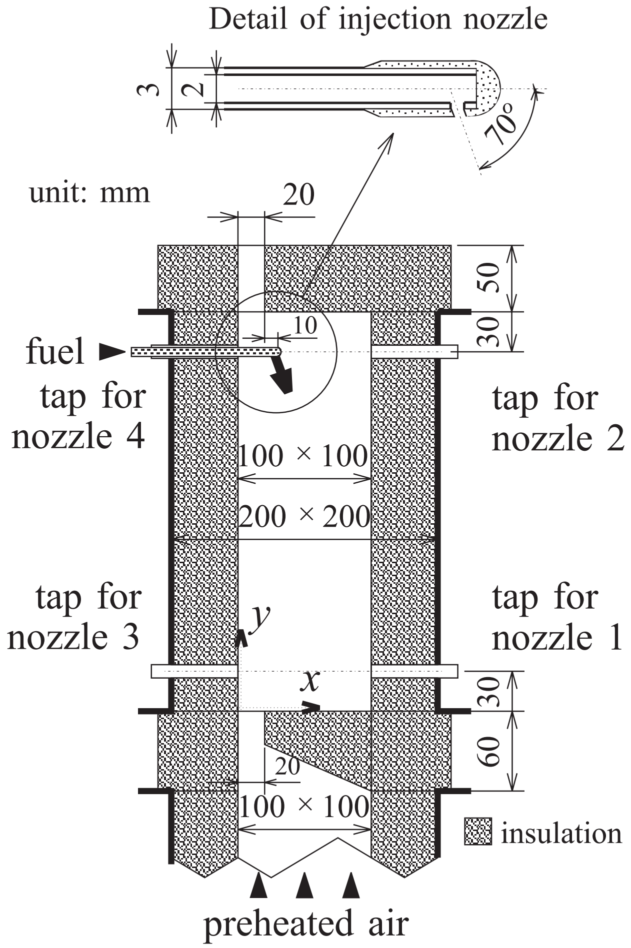

Fig. 6. Combustion chamber used in the experiment.

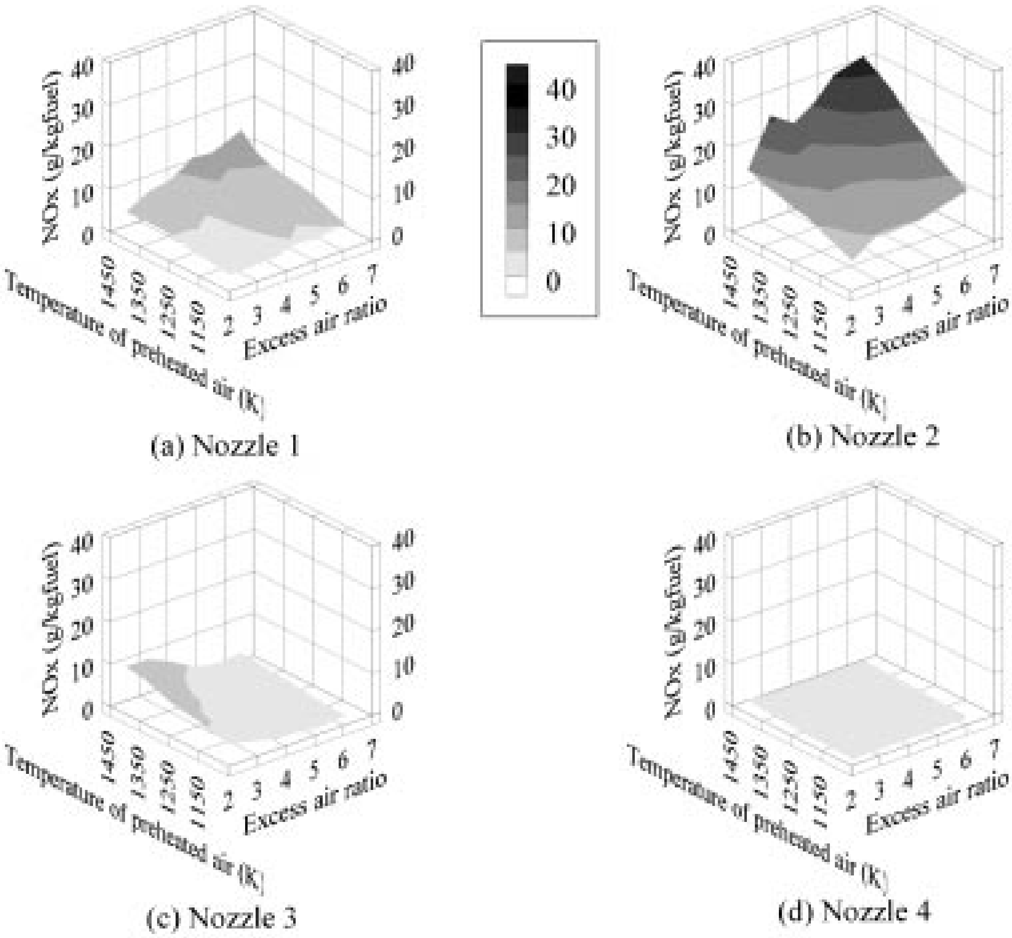

Fig. 7. Influence of inlet air temperature and global excess air ratio on nitric oxide emission.

the recirculating flow. The fuel injection rate was kept constant at $0.06L_{\mathrm{N}}\ \mathrm{s}^{-1}$, the flow rate of combustion air was varied between 1.5 and $4.0L_{\mathrm{N}}\ \mathrm{s}^{-1}$ at standard condition and the temperature was maintained between 1073 and 1423 K. The point is that we intended to change the mixing process in the combustion chamber by changing the fuel nozzle position while keeping the air flow pattern constant.

Fig. 7 shows the variation of emission index of nitric oxides at the exit of the combustion chamber versus combustion air temperature and global excess air ratio. Since the fuel injection rate was kept constant, the global excess air ratio can be related to the inlet air velocity. A drastic change of nitric oxide emission was observed by changing only the location of the fuel nozzle. The tendency of the emission index in terms of global excess air ratio for fuel nozzle 3 was quite different from those for the cases of fuel nozzles 1 and 2. Further, for fuel nozzle 4, the emission level was extremely low compared to that at any other operating condition and showed scarce dependence on either global excess air ratio or combustion air temperature. However small it

might be, the temperature rise of the combustion air increased nitric oxide emission for all nozzle positions. The decrease in nitric oxide emission should not be ascribed to imperfect combustion because no unburned hydrocarbons were detected at the exit of the exhaust for all cases. Therefore, it is reasonably understood that the flame structure or combustion regime was affected by the change of fuel nozzle location, because other experimental parameters, such as global excess air ratio and combustion air temperature, were kept the same. This fact seems to contradict the existing explanation that the reduction of nitric oxide emission can hardly be expected for non-premixed combustion because the combustion reaction always takes place at near-stoichiometric condition, even in large excess air ratio operation.

What is the main reason for the reduction of nitric oxides emission in these cases? We can point out the following factors as possible causes: (a) low oxygen concentration, (b) low flame temperature and (c) decomposition of nitric oxides. However, judging from the experiments described above, the mixing process between the fuel and preheated air or burned gas is considered to be the most influencing factor. Namely, the change of recirculation rate of the burned gas results in the change of oxygen concentration in the reaction zone and the flame temperature, even if the flow rates of fuel and air are kept the same.

To investigate the temperature field, we measured fluctuating temperatures with a fine thermocouple of 25 μm (Pt/Pt–Rh13%) coated with SiO2, whose time constant of frequency response was electrically compensated [27]. Fig. 8 shows the temperature fluctuations at the point of the highest time-averaged temperature obtained for each fuel nozzle location. The corresponding time-averaged temperature and RMS value are written in each figure.

For fuel nozzle 2, the instantaneous high temperature peaks appear frequently, and they sometimes exceed 2000 K. These result from the larger fluctuations on the higher time-averaged temperature than for any other nozzle position. In addition, we notice small wavy fluctuations of low frequency exist in the waveform record. For fuel nozzles 3 and 4, the time-averaged temperatures are lower than for fuel nozzles 1 and 2, and the low frequency fluctuations are seldom seen. For any fuel nozzle position, the RMS values of the temperature fluctuations are between 40 to 75 K, which is not so large as that usually seen in a typical turbulent non-premixed flame burning in atmospheric air. Therefore, from the fact that the temperature difference between the preheated oxidizer and the flame was relatively small compared to ordinary atmospheric air combustion, we understand that combustion takes place in low oxygen circumstances, resulting from dilution with plenty of recirculated burned gas in the combustion chamber.

In general, the nitric oxide emission depends on the flame temperature and residence time in the high temperature region. A significant amount of nitric oxides must be generated even in a short residence time when the flame temperature is higher than usual. Therefore, not only the time-averaged temperature level but also its fluctuation intensity, which defines its instantaneous peak temperature, plays an influential role on nitric oxide emission. Based on this thought, the observed trend in exhaust emission index among the four cases can be reasonably interpreted by the cumulative frequency distributions of fluctuating temperature. Fig. 9 shows the cumulative frequency distributions of the fluctuating temperatures shown in Fig. 8. Although the waveforms for 1 s are shown Fig. 8, the results of the statistics are obtained based on the data for 4 s. For fuel nozzle 4, although the instantaneous maximum temperature was recorded as 1851 K, the probability of such a high temperature is quite low, and most of the temperatures are below 1800 K. The probabilities of the high temperatures exceeding 1800 K for fuel nozzles 3, 1 and 2 are 5%,

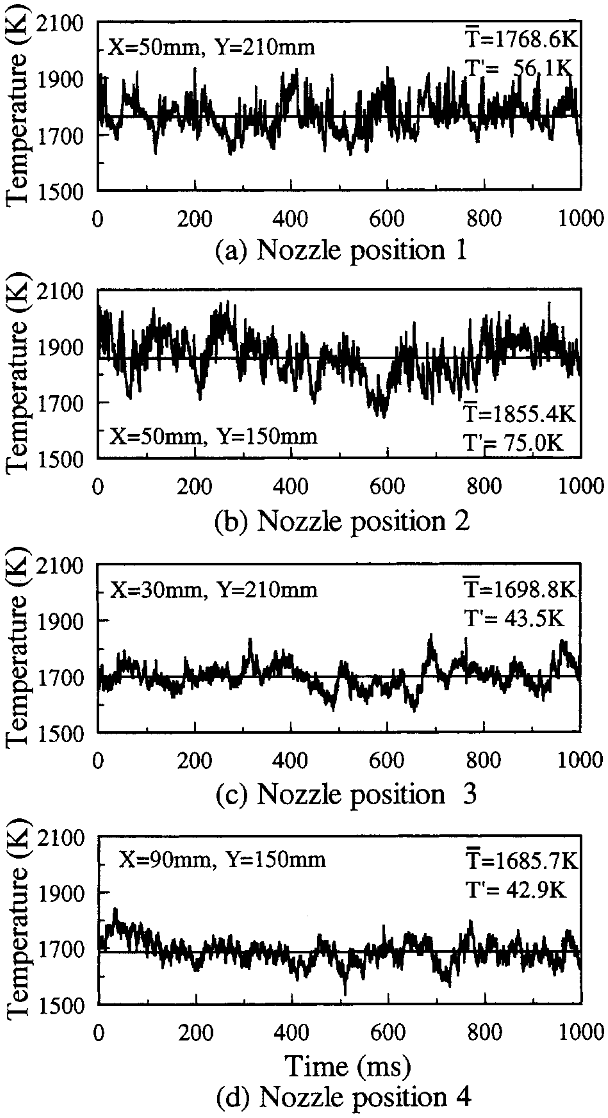

Fig. 8. Temperature fluctuations at the point of maximum time averaged temperature.

30% and 75%, respectively, and some probabilities over 2000 K are indicated, particularly for fuel nozzle 2. These values are strongly related to the nitric oxide emission shown in Fig. 7. It is important to lower the intensity of temperature fluctuations as well as the mean temperature level.

The observation above showed us that the flame temperature of non-premixed flames is strongly dependent on the mixing process of the combustion air with the burned gases, namely the dilution of air with burned products. Accordingly, it is possible to generate lower temperature flames by the use of highly preheated air associated with a high rate of burned gas recirculation, rather than the ordinary flame burning with atmospheric air.

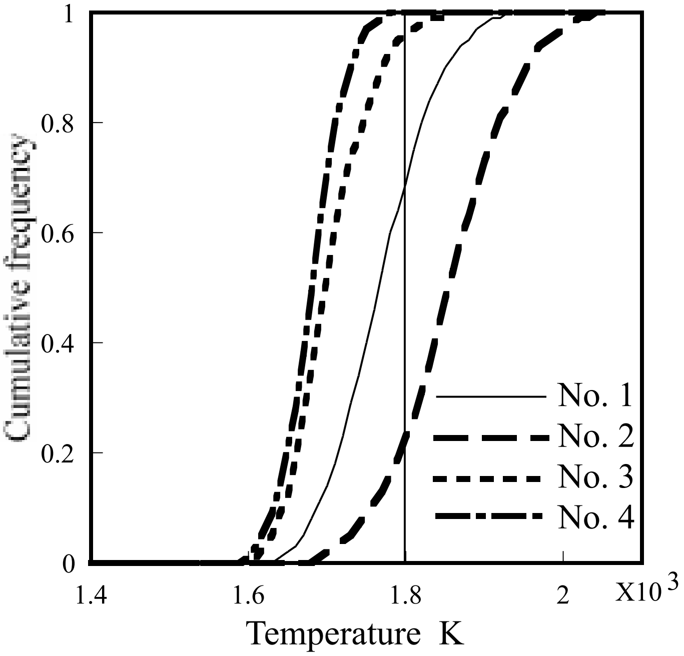

Fig. 9. Cumulative frequency distributions of temperature fluctuations at the maximum time averaged temperature.

5. Advanced low NO_x combustion using highly preheated air

If we consider the primary reason for the lowered nitric oxide emission in the present and former experiments as ascribed to the combination of highly preheated combustion air and high momentum injection of staged combustion air, we can understand the importance of generating low oxygen diluted air before the combustion. This kind of combustion in low content of oxygen can be sustained only by a supply of highly preheated air because the temperature of the diluted air, with a high rate of burned gas recirculation, should be higher than the auto-ignition temperature shown in Fig. 5. If atmospheric air is used for this type of low oxygen combustion, combustion never occurs in the furnace. Accordingly, advanced low NO_x technology becomes possible if we use highly preheated air whose temperature is high enough for auto-ignition when it is diluted with recirculated burned gases (Fig. 10).

In the developing process of a high performance industrial furnace, highly preheated air combustion and its practical application as an advanced low NO_x technology were demonstrated successfully [28–31]. However, the applied area was limited, so far, to high temperature furnaces where this technology can be easily applied. Therefore, it is necessary to try wider applications of this attractive technology.

Here is a typical view, insisting that there is no advantage to adopt regenerative burners in such a heating system emitting low temperature exhaust like a boiler, because neither a large increase of thermal efficiency nor sufficient preheating of combustion air can be expected by regeneration.

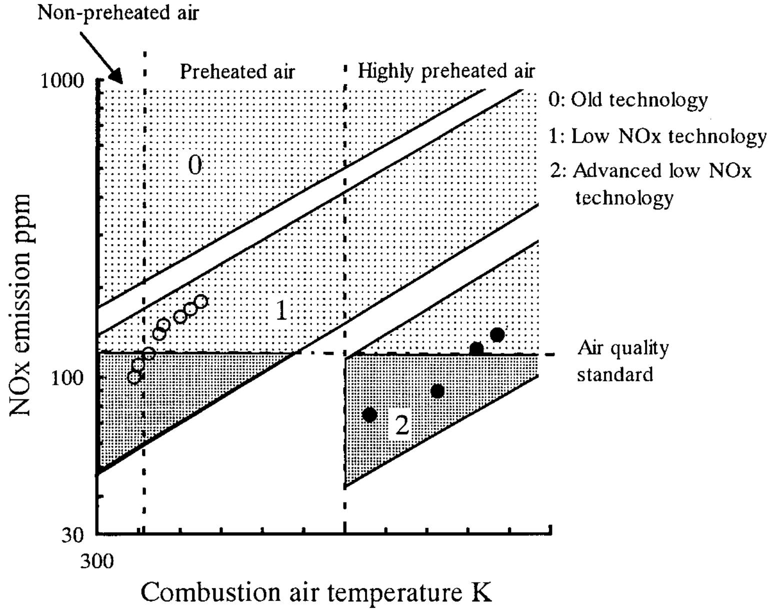

Fig. 10. Correlation between combustion air temperature and NO_x control technology (Symbols are from Ref. [24]).

This view is quite reasonable from an economical point of view. However, if nitric oxide emission can be reduced dramatically without any decrease in thermal efficiency, it is worth developing as a future technology from an ecological point of view.

Considering the heat utilization processes in a boiler starting from the heat release due to combustion to the exhaust, the temperature varies typically from approximately 1800 down to 400 K. Namely, there is always the appropriate temperature on the way, which is high enough for highly preheated air combustion, although the final exhaust temperature is insufficient for regenerative combustion. Therefore, we divide the burned gas flow into two parts at a high temperature level sufficient for highly preheated air combustion and utilize one part for the heat regeneration system and the other part for the boiler. Since the stored heat in the regenerator is recycled into the boiler in the following cycle, there is no decline in thermal efficiency, as far as a change of heat loss is taken into account. The point is the exhaust gas temperature leaving the regenerator. If the temperature is lower than the exhaust temperature of the boiler, it is no problem. In case of the higher temperature, a heat recovery device like a water pre-heater should be added to the system. Thus, in Fig. 11, we can demonstrate an example of an advanced low NO_x boiler having the same thermal efficiency as existing types.

There are a variety of combustion or heating systems, such as a boiler and a tube heater, whose exhaust gas temperature is lower than the auto-ignition temperature of the fuel. Nevertheless, it is possible to design a heat regenerative combustion process associated with highly preheated air as demonstrated above. We believe that it is worth making an effort to apply the concept of highly preheated air combustion to new fields, such as gas turbines and Diesel engines, where combustion methods are quite different from those in industrial furnaces.

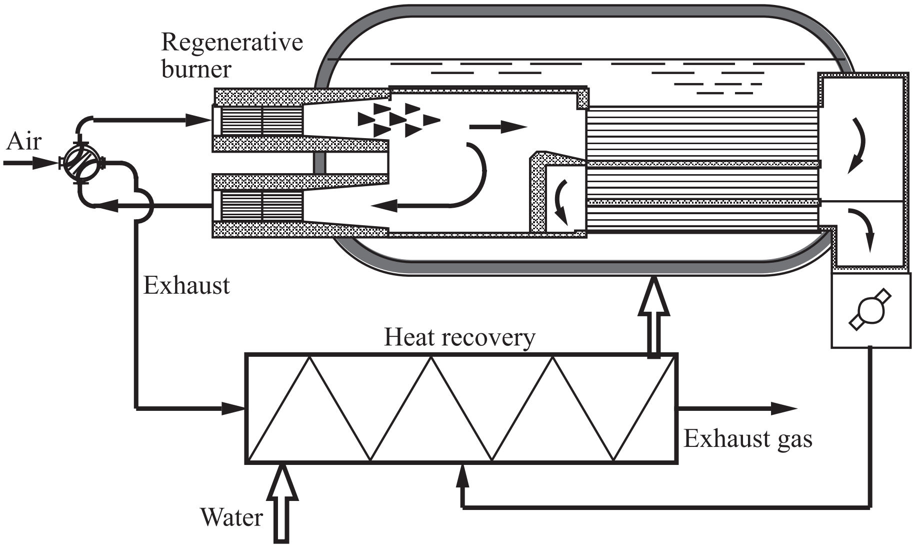

Fig. 11. Boiler with optimized regenerative burner system (schematic).

6. Conclusion

The performance of a high frequency alternating flow type regenerator as a heat recovery system has been proved quite high in achieving a high degree of energy saving. It keeps exhaust gas temperatures sufficiently low and raises the fresh air temperature up to almost the furnace exit temperature, as if a thermal dam were built at the furnace exit. Another attractive characteristic of the regenerative furnace is extremely low nitric oxide emission, notwithstanding highly preheating the combustion air. It has been clarified that combustion can take place in an extremely low concentration of oxygen if the combustion air is preheated sufficiently higher than the auto-ignition temperature of the fuel. The low oxygen content in the oxidizer is obtained a mixing control of preheated combustion air with burned gas in the furnace. Dilution makes the oxygen content of the oxidizer low, which decreases temperature fluctuations in the flame as well as the mean temperature, hence, low nitric oxide emission.

Since it seems possible to apply the concept to new fields as demonstrated above, further efforts of practical applications of this technology to other combustion devices and systems are expected in the future.

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